

# Measurement of the spectral function for the $\tau^- \rightarrow K^- K_S \nu_\tau$ decay

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(Received 28 June 2018; published 16 August 2018)

The decay  $\tau^- \rightarrow K^- K_S \nu_\tau$  has been studied using  $430 \times 10^6 e^+ e^- \rightarrow \tau^+ \tau^-$  events produced at a center-of-mass energy around 10.6 GeV at the PEP-II collider and studied with the *BABAR* detector. The mass spectrum of the  $K^- K_S$  system has been measured and the spectral function has been obtained. The measured branching fraction  $\mathcal{B}(\tau^- \rightarrow K^- K_S \nu_\tau) = (0.739 \pm 0.011(\text{stat}) \pm 0.020(\text{syst})) \times 10^{-3}$  is found to be in agreement with earlier measurements.

DOI: 10.1103/PhysRevD.98.032010

## I. INTRODUCTION

The  $\tau$  lepton provides a remarkable laboratory for studying many open questions in particle physics. With a large statistics of about  $10^9$   $\tau$ 's produced in  $e^+ e^-$  annihilation at the *BABAR* experiment, various aspects can be studied, e.g., improving the precision of spectral functions describing the mass distribution of the hadronic decays of the  $\tau$ . In this work, we analyze the  $\tau^- \rightarrow K^- K_S \nu_\tau$  decay<sup>1</sup> and measure the spectral function of this channel defined as [1]

$$V(q) = \frac{m_\tau^8}{12\pi C(q)|V_{ud}|^2} \frac{\mathcal{B}(\tau^- \rightarrow K^- K_S \nu_\tau)}{\mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} \frac{1}{N} \frac{dN}{dq}, \quad (1)$$

where  $m_\tau$  is the  $\tau$  mass [2],  $q \equiv m_{K^- K_S}$  is the invariant mass of the  $K^- K_S$  system,  $V_{ud}$  is an element of the Cabibbo-Kobayashi-Maskawa matrix [2],  $(dN/dq)/N$  is the normalized  $K^- K_S$  mass spectrum, and  $C(q)$  is the phase space correction factor given by the following formula:

$$C(q) = q(m_\tau^2 - q^2)^2(m_\tau^2 + 2q^2). \quad (2)$$

According to the conserved-vector-current hypothesis [1], the  $\tau^- \rightarrow K^- K_S \nu_\tau$  spectral function is related to the isovector part ( $I = 1$ ) of the  $e^+ e^- \rightarrow K \bar{K}$  cross section:

$$\sigma_{e^+ e^- \rightarrow K \bar{K}}^{I=1}(q) = \frac{4\pi^2 \alpha^2}{q^2} V(q), \quad (3)$$

where  $\alpha$  is the fine structure constant. The cross sections  $e^+ e^- \rightarrow K^+ K^-$  and  $e^+ e^- \rightarrow K_S K_L$  have been recently measured by the *BABAR* [3,4] and SND experiments [5]. Combining data from the  $\tau^- \rightarrow K^- K_S \nu_\tau$  with  $e^+ e^- \rightarrow K \bar{K}$  measurements, the moduli of the isovector and isoscalar form factors and the relative phase between them can be obtained in a model-independent way.

The branching fraction for the  $\tau^- \rightarrow K^- K_S \nu_\tau$  decay has been measured with relatively high (3%) precision by the Belle experiment [6]. The  $K^- K_S$  mass spectrum was measured by the CLEO experiment [7]. In the CLEO analysis, a data set of  $2.7 \times 10^6$  produced  $\tau$  pairs was used, and about 100 events in the decay channel  $\tau^- \rightarrow K^- K_S \nu_\tau$  were selected. In this work, using about  $\sim 10^9$   $\tau$  leptons, we significantly improve upon the measurement of the spectral function for the  $\tau^- \rightarrow K^- K_S \nu_\tau$  decay.

## II. DATA USED IN THE ANALYSIS

We analyze a data sample corresponding to an integrated luminosity of  $468 \text{ fb}^{-1}$  recorded with the *BABAR* detector [8,9] at the SLAC PEP-II asymmetric-energy  $e^+ e^-$  collider.

For simulation of  $e^+ e^- \rightarrow \tau^+ \tau^-$  events the KK2f Monte Carlo generator [10] is used, which includes higher-order radiative corrections to the Born-level process. Decays of  $\tau$  leptons are simulated using the Tauola package [11]. Two separate samples of simulated  $e^+ e^- \rightarrow \tau^+ \tau^-$  events are used: a generic sample with  $\tau$  decaying to all

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<sup>1</sup>Throughout this paper, inclusion of charge-conjugated channels is implied.

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significant final states, and the signal channel where  $\tau^+ \rightarrow l^+ \nu_l \bar{\nu}_\tau$ ,  $l = e$  or  $\mu$  and  $\tau^- \rightarrow K^- K_S \nu_\tau$ . To estimate backgrounds, we use a sample of simulated generic  $e^+e^- \rightarrow \tau^+\tau^-$  events after excluding the signal decay channel ( $\tau^+\tau^-$  background) and a sample containing all events arising from  $e^+e^- \rightarrow q\bar{q}$ ,  $q = u, d, s, c$  and  $e^+e^- \rightarrow B\bar{B}$  processes ( $q\bar{q}$  background). The  $q\bar{q}$  background events with  $q = u, d, s, c$  are generated using the JETSET generator [12], while  $B\bar{B}$  events are simulated with EVTGEN [13]. The detector response is simulated with GEANT4 [14]. The equivalent luminosity of the simulated sample is 2-3 times higher than the integrated luminosity in data.

### III. EVENT SELECTION

We select  $e^+e^- \rightarrow \tau^+\tau^-$  events with the  $\tau^+$  decaying leptonically ( $\tau^+ \rightarrow l^+ \nu_l \bar{\nu}_\tau$ ,  $l = e$  or  $\mu$ ) and the  $\tau^-$  decaying to  $K^- K_S \nu_\tau$ . Such events referred to as signal events below. The  $K_S$  candidate is detected in the  $K_S \rightarrow \pi^+\pi^-$  decay mode. The topology of events to be selected is shown in Fig. 1. Unless otherwise stated, all quantities are measured in the laboratory frame. The selected events must satisfy the following requirements:

- (i) The total number of charged tracks,  $N_{\text{trk}}$ , must be four and the total charge of the event must be zero.
- (ii) Among the four charged tracks there must be an identified lepton (electron or muon) and an identified kaon of opposite charge. The track origin point requirements are  $|d_0| < 1.5$  cm and  $|z_0| < 2.5$  cm, where  $|d_0|$  and  $|z_0|$  are the distances between the track and the interaction region center in transverse and longitudinal directions with respect to the beams.
- (iii) To reject  $\mu$  pairs and Bhabha events, the lepton candidate must have a momentum above 1.2 GeV/c, the momentum in the center-of-mass

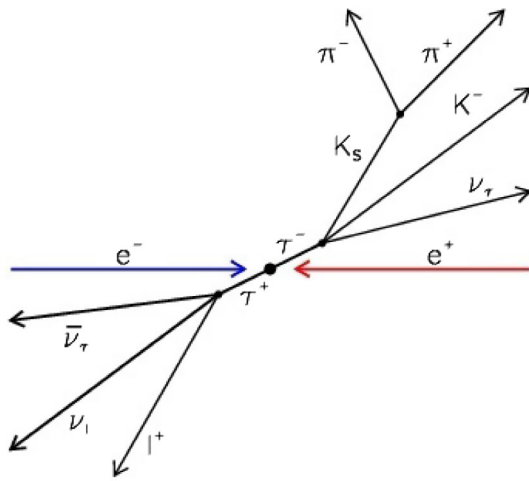


FIG. 1. Schematic view of the  $\tau$  decay chains in  $e^+e^- \rightarrow \tau^+\tau^-$  events selected for this analysis. Lepton  $l^+$  can be electron or muon.

frame (c.m. momentum) must be smaller than 4.5 GeV/c, and the cosine of the lepton polar angle  $|\cos \theta_l|$  must be below 0.9.

- (iv) To suppress background from charged pions, the charged kaon candidate must have a momentum,  $p_K$ , above 0.4 GeV/c and below 5 GeV/c, and the cosine of its polar angle must lie between  $-0.7374$  and  $0.9005$ .
- (v) The two remaining tracks, assumed to be pions, form the  $K_S$  candidate. The  $\pi^+\pi^-$  invariant mass must lie within 25 MeV/ $c^2$  of the nominal  $K_S$  mass, 497.6 MeV/ $c^2$ . The  $K_S$  flight length  $r_{K_S}$ , measured as the distance between the  $\pi^+\pi^-$  vertex and the collision point, must be larger than 1 cm. The  $r_{K_S}$  distributions for data events and simulated signal events are shown in Fig. 2.
- (vi) The total energy in neutral clusters,  $\Sigma E_\gamma$ , must be less than 2 GeV (Fig. 3). Here, a neutral cluster is defined as a local energy deposit in the calorimeter with energy above 20 MeV and no associated charged track.
- (vii) The magnitude of the thrust [15,16] for the event, calculated using charged tracks only, must be greater than 0.875.
- (viii) The angle defined by the momentum of the lepton and that of the  $K^- K_S$  system in the c.m. frame must be larger than 110 degrees.

As a result of applying these selection criteria the  $\tau$  background is suppressed by 3.5 orders of magnitude, and the  $q\bar{q}$  background by 5.5 orders.

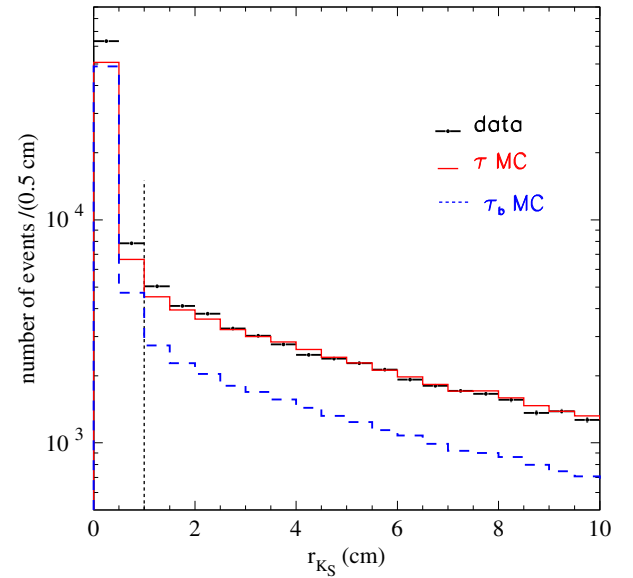


FIG. 2. The  $K_S$  candidates decay length distribution for data (points with errors),  $\tau^+\tau^-$  simulation events (solid histogram), and  $\tau$  background simulation (dashed histogram). The vertical line indicates the boundary of the selection condition.



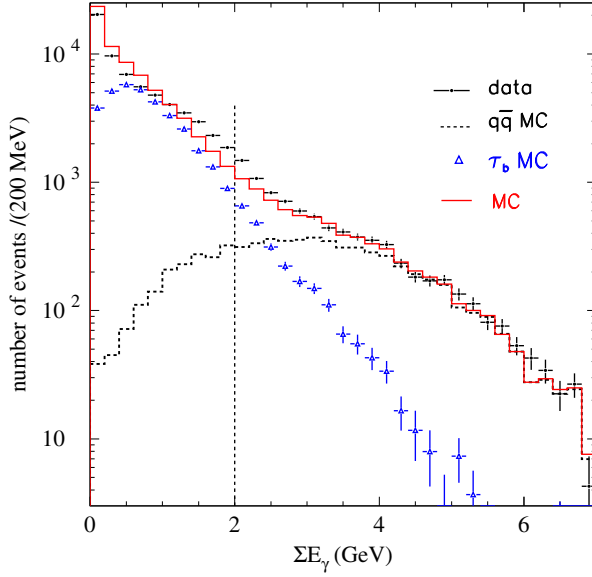


FIG. 3. Distributions of the total energy of photons in the event for data (points with errors),  $\tau^+\tau^-$  and  $q\bar{q}$  simulation events (solid histogram),  $\tau$  background simulation (empty triangles with errors) and  $q\bar{q}$  background simulation (dashed histogram). The vertical line indicates the boundary of the selection condition.

#### IV. DETECTION EFFICIENCY

The detection efficiency obtained after applying the selection criteria is calculated using signal Monte Carlo simulation as a function of the true  $m_{K^-K_S}$  mass and is shown in Fig. 4. The efficiency is weakly dependent on  $m_{K^-K_S}$ . The average efficiency over the mass spectrum is about 13%. It should be noted that the  $K^-K_S$  mass

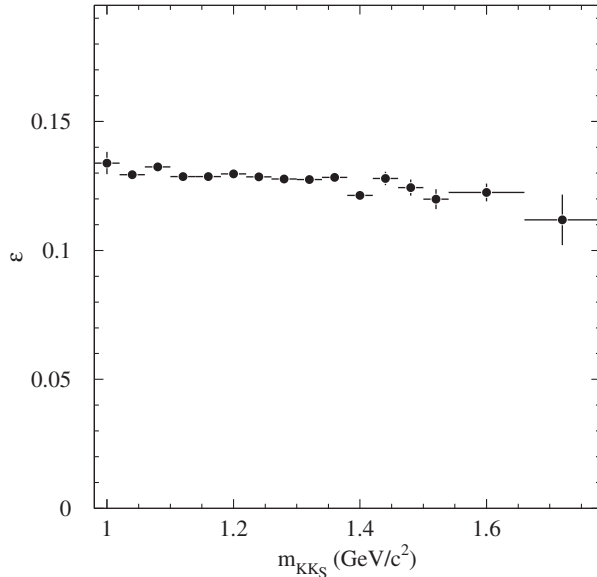


FIG. 4. Selection efficiency as a function of the  $K^-K_S$  invariant mass, according to simulation.

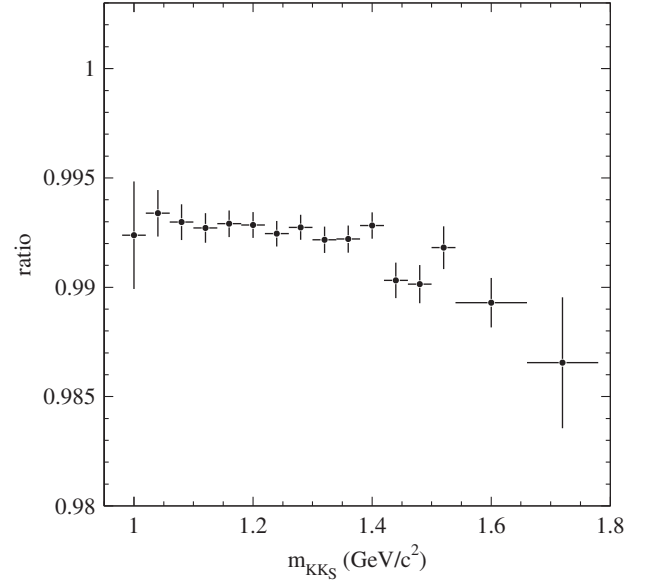


FIG. 5. Efficiency correction factor for adjusting the simulation PID efficiency to match the efficiency measured on data, as a function of the  $K^-K_S$  mass for signal events.

resolution is about  $2\text{--}3 \text{ MeV}/c^2$ , significantly smaller than the size of the mass bin ( $40 \text{ MeV}/c^2$ ) used in Fig. 4. Therefore, in the following we neglect the effects of the finite  $K^-K_S$  mass resolution.

To correct for the imperfect simulation of the kaon identification requirement, the particle identification (PID) efficiencies have been compared for data and simulation on high purity control samples of kaons from  $D^* \rightarrow \pi^+ D^0$ ,  $D^0 \rightarrow K^- \pi^+$  decays [17]. We correct the simulated efficiency using the measured ratios of the efficiencies measured in data and Monte Carlo, in bins of the kaon candidate momentum and polar angle. The resulting correction factor as a function of  $m_{K^-K_S}$  is shown in Fig. 5.

#### V. SUBTRACTION OF NON- $K_S$ BACKGROUND

The  $\pi^+\pi^-$  mass spectra for  $K_S$  candidates in data and simulated signal events are shown in Fig. 6. The data spectrum consists of a peak at the  $K_S$  mass and a flat background. To subtract the non- $K_S$  background, the following procedure is used. The signal region is set to  $\pi^+\pi^-$  masses within  $0.0125 \text{ GeV}/c^2$  of the  $K_S$  mass (indicated by arrows in Fig. 6), and the sidebands are set to between  $0.0125$  and  $0.0250 \text{ GeV}/c^2$  away from the nominal  $K_S$  mass. Let  $\beta$  be the fraction of events with a true  $K_S$  that fall in the sidebands, and let  $\alpha$  be the fraction of non- $K_S$  events that fall in the sidebands. The total number of events in the signal region plus the sidebands,  $N$ , and the number of events in the sidebands,  $N_{sb}$ , depend on the number of true  $K_S$ ,  $N_{K_S}$ , and the number of non- $K_S$  background events,  $N_b$  according to the following relation:

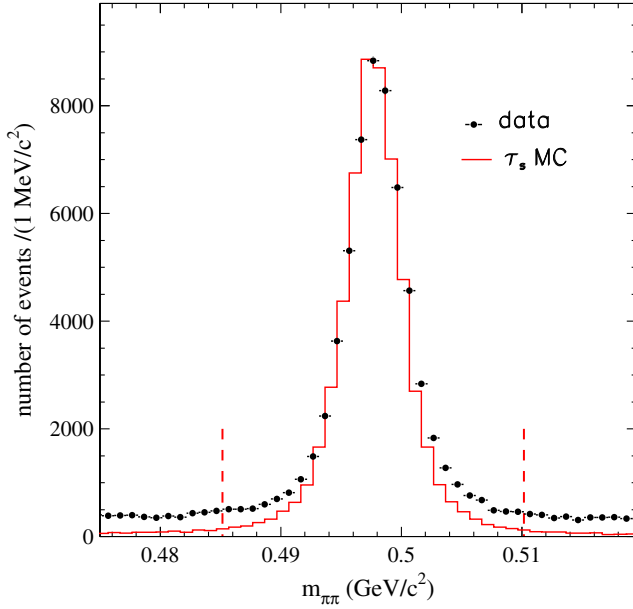


FIG. 6. The  $\pi^+\pi^-$  mass spectrum for  $K_S$  candidates in data (points with errors) and signal simulation (histogram). Between the two vertical lines there is a signal region used in the procedure of non- $K_S$  background subtraction.

$$N = N_{K_S} + N_b, \quad (4a)$$

$$N_{sb} = \alpha \cdot N_b + \beta \cdot N_{K_S} \quad (4b)$$

Therefore:

$$N_{K_S} = (\alpha N - N_{sb}) / (\alpha - \beta). \quad (5)$$

The value of  $\beta$  is determined using  $\tau$  signal simulation. It is found to be nearly independent of the  $m_{K-K_S}$  mass and is equal to  $0.0315 \pm 0.0015$ . The value of  $\alpha$  is expected to be 0.5 for a uniformly distributed background. This is consistent with the value  $0.499 \pm 0.005$  obtained on simulated  $\tau^+\tau^-$  background events. The non- $K_S$  background is subtracted in each  $m_{K-K_S}$  bin. Its fraction is found to be about 10% of the selected events with  $m_{K-K_S}$  near and below  $1.3 \text{ GeV}/c^2$  and increases up to 50% above  $1.6 \text{ GeV}/c^2$ .

## VI. SUBTRACTION OF $\tau$ -BACKGROUND WITH A $\pi^0$

Although the studied process  $\tau^- \rightarrow K^- K_S \nu_\tau$  is not supposed to contain a  $\pi^0$  in the final state, some events from background processes with a  $\pi^0$  pass the selection criteria. In the following, we describe how the  $\pi^0$  background contribution is subtracted.

The  $K^- K_S$  mass spectra for selected data and  $\tau^+\tau^-$  simulated events after subtraction of the non- $K_S$  background are shown in Fig. 7. According to the simulation, the number

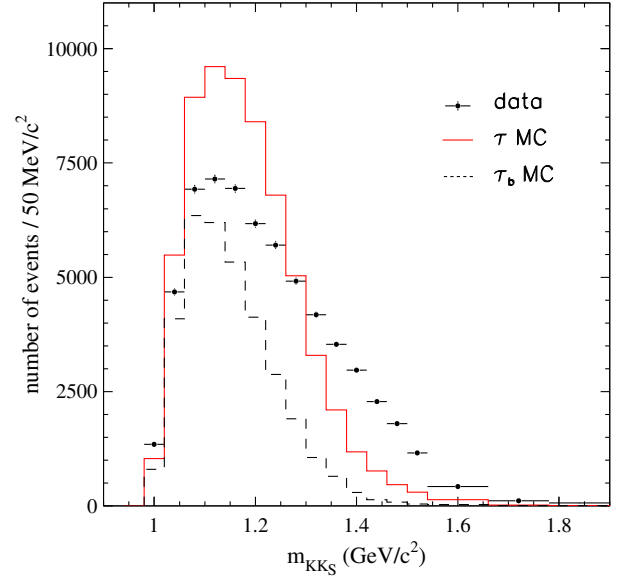


FIG. 7. The  $m_{K-K_S}$  spectra for data (points with errors),  $\tau^+\tau^-$  simulation events (solid histogram), and  $\tau$  background simulation (dashed histogram). The non- $K_S$  background is subtracted.

of signal and  $\tau$ -background events are of the same order of magnitude. The  $\tau^+\tau^-$  background consists of events with the decay  $\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$  (79%), events with a misidentified kaon from decays  $\tau^- \rightarrow \pi^- K_S \nu_\tau$  (10%) and  $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_\tau$  (3%), and events with a misidentified lepton mainly from the decays  $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$  and  $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$  (7%). Thus, more than 80% of the background events contain a  $\pi^0$  in the final state. It should be noted that events with a misidentified lepton have the same  $m_{K-K_S}$  distribution as signal events.

The branching fractions for the background modes without a  $\pi^0$ ,  $\tau^- \rightarrow \pi^- K_S \nu_\tau$  and  $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$ , have been measured with high precision (1.7% and 0.5%) [2]. The hadronic mass spectrum for  $\tau^- \rightarrow \pi^- K_S \nu_\tau$  is also well known [18] and this decay proceeds mainly via the  $K^*(892)$  intermediate state. Therefore all  $\tau^+\tau^-$  background without a  $\pi^0$  is subtracted using Monte Carlo simulation. The amount of  $q\bar{q}$  background, not shown in Fig. 7, is about 2% of selected data events. The part of this background without a  $\pi^0$  is also subtracted using Monte Carlo simulation.

The branching fractions for the background modes  $\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$ ,  $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_\tau$ , and  $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}_\tau$  are measured with a precision of 4.7%, 3.4%, and 0.4%, respectively. The hadronic mass spectrum is well known only for the last decay [19]. For the two other decays, only low-statistics measurements [7] are available. Therefore, we use the data to subtract the  $\tau$ -background with  $\pi^0$  from the  $K^- K_S$  mass spectrum. To do this, the selected events are divided into two classes, without and with a  $\pi^0$  candidate, which is defined as a pair of photons with an invariant mass in the range 100–160  $\text{MeV}/c^2$ .

On the resulting sample, the numbers of signal ( $N_s$ ) and background  $\tau^+\tau^-$  events containing a  $\pi^0$  candidate ( $N_b$ ) are obtained in each  $m_{K^-K_S}$  bin:

$$N_{0\pi^0} = (1 - \epsilon_s)N_s + (1 - \epsilon_b)N_b, \quad (6a)$$

$$N_{1\pi^0} = \epsilon_s N_s + \epsilon_b N_b, \quad (6b)$$

where  $N_{0\pi^0}$  and  $N_{1\pi^0}$  are the numbers of selected data events with zero and at least one  $\pi^0$  candidate, and  $\epsilon_s$  ( $\epsilon_b$ ) is the probability for signal (background)  $\tau^+\tau^-$  events to be found in events with at least one  $\pi^0$  candidate calculated using Monte Carlo simulation. The values  $\epsilon_s$  and  $\epsilon_b$  for each bin in  $m_{K^-K_S}$  are measured in Monte Carlo by counting how many signal and background event candidates contain a  $\pi^0$  candidate. Figure 8 shows the  $\epsilon_s$  and  $\epsilon_b$  measured in Monte Carlo as a function of  $m_{K^-K_S}$ . The efficiency  $\epsilon_b$  is corrected to take into account the different  $\pi^0$  efficiency between data and Monte Carlo as measured on data and simulated control samples in the ISR  $e^+e^- \rightarrow \omega(783)\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$  process [20]. The average correction is  $\delta = 0.976 \pm 0.008$ . The non-zero value of  $\epsilon_s$  is due to random combinations of two spurious photons originating from beam background or nuclear interactions of charged kaons or pions. The beam-generated background is simulated by using special background events recorded during normal data-taking conditions but with a randomly generated trigger. These events are superimposed on simulated events. The following procedure is used to measure  $\epsilon_s$  on data events. We compare the solution of Eqs. (6a) and (6b) described above with the solution of the same system, in which the number of events with  $\pi^0$  is determined from the

fit to the two-photon invariant mass spectrum of  $\pi^0$  candidates. Since the mass dependence of  $\epsilon_s$  and  $\epsilon_b$  is mild (Fig. 8), this comparison is performed using the full sample of selected events without splitting the sample into  $K^-K_S$  mass bins. The two-photon mass spectrum of  $\pi^0$  candidates in data is shown in Fig. 9.

The spectrum in Fig. 9 is fitted by a sum of a Gaussian and a flat component. The numbers  $N_{1\pi^0}$  and  $N_{0\pi^0}$  on the left side of Eqs. (6a) and (6b) are substituted by  $N_{1\pi^0}^* = N_{1\pi^0} - N_{1\pi^0}^{\text{lin}}$  and  $N_{0\pi^0}^* = N_{0\pi^0} + N_{1\pi^0}^{\text{lin}}$ , where  $N_{1\pi^0}^{\text{lin}}$  is the number of events under the flat component, obtained after fitting the  $\gamma\gamma$  spectrum in Fig. 9. The value  $\epsilon_b$  is substituted by  $\epsilon_b^* = w\epsilon_b$ , where  $w = 0.682 \pm 0.010$  is the fraction of events with a reconstructed  $\pi^0$  for simulated  $\tau^+\tau^-$  background (Fig. 9). The term “reconstructed  $\pi^0$ ” corresponds to  $\pi^0$ ’s in the Gaussian part in Fig. 9. The modified system of equations is

$$N_{0\pi^0}^* = N_s + (1 - \epsilon_b^*)N_b, \quad (7a)$$

$$N_{1\pi^0}^* = \epsilon_b^* N_b. \quad (7b)$$

In Eqs. (7a) and (7b) the top line contains all events without a reconstructed  $\pi^0$ , while the lower line contains events with at least one reconstructed  $\pi^0$ . After subtracting the spurious  $\pi^0$ ’s corresponding to the flat background in Fig. 9, Eqs. (7a) and (7b) no longer contains  $\epsilon_s$  nor a contribution from the  $\pi^0$  background.

The average value of  $\epsilon_b$  from Fig. 8 is  $0.720 \pm 0.003$ , giving  $\epsilon_b^* = 0.491 \pm 0.008$  on the average. This value is then corrected by the reconstructed  $\pi^0$  efficiency correction

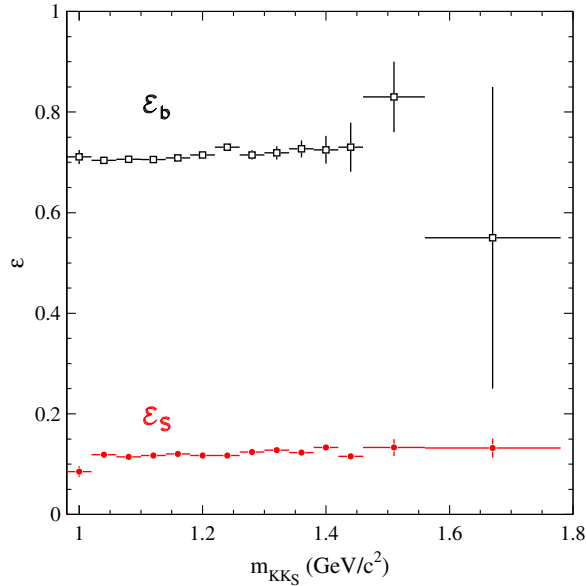


FIG. 8. The probabilities  $\epsilon_s$  and  $\epsilon_b$  used in Eqs. (6a) and (6b) as functions of the  $K^-K_S$  mass, measured on simulated events.

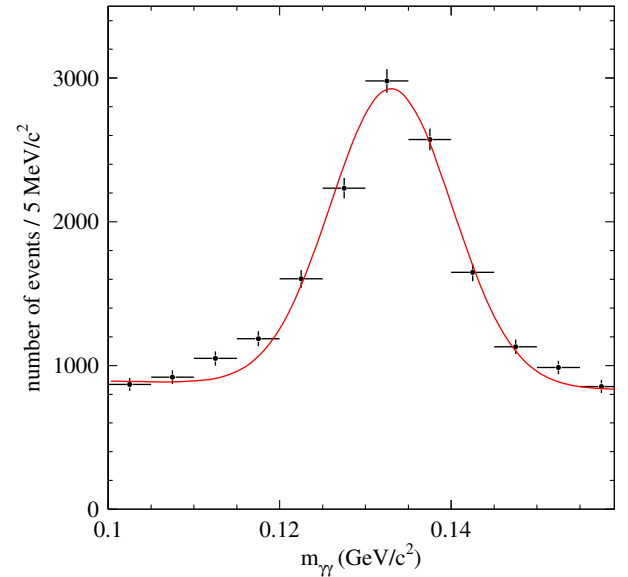


FIG. 9. Two-photon invariant mass spectrum of  $\pi^0$  candidates in data. The curve corresponds to the fit function, described in text.

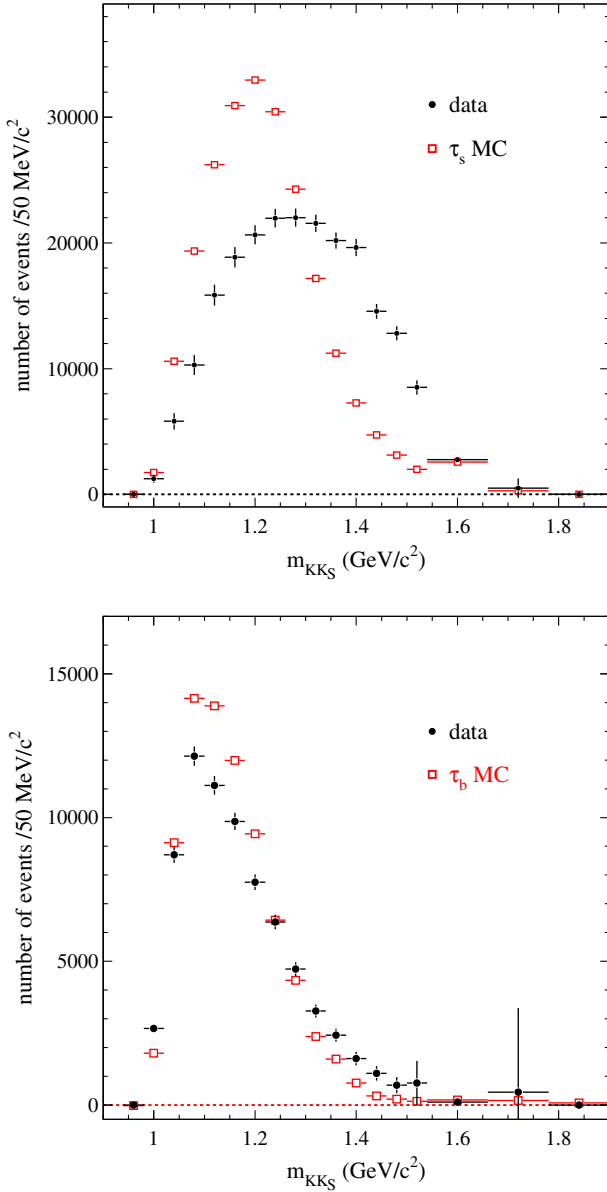


FIG. 10. Measured  $m_{K^-K_S}$  spectra for signal events (top) and  $\tau$  background events with  $\pi^0$  (bottom) in comparison with the  $\tau$  signal ( $\tau_S$ ) and  $\tau$  background ( $\tau_b$ ) Monte Carlo simulation.

factor  $\delta$ , as discussed above. The number of signal events,  $N_s$ , obtained by solving Eqs. (7a) and (7b) and using the corrected value of  $\epsilon_b^*$  is about 1% higher than the previous one, derived from Eqs. (6a) and (6b). This 1% shift in  $N_s$  is explained by the difference between data and Monte Carlo simulation in  $\epsilon_s$ .

To obtain the final  $K^-K_S$  mass spectrum we return to Eqs. (6a) and (6b). Based on the above study of the  $\pi^0$  systematics we must correct the efficiencies  $\epsilon_s$  and  $\epsilon_b$ . First, we correct the value of  $\epsilon_b$  by the  $\pi^0$  efficiency correction  $1 - w(1 - \delta) \simeq 0.984 \pm 0.006$ , where  $w$  and  $\delta$  are defined above. Then we adjust the value of  $\epsilon_s$  by a factor  $1.05 \pm 0.05$  to take into account the above-mentioned 1%

correction in flat background simulation. Then the number of simulated  $\tau^+\tau^-$  background events without a  $\pi^0$  is multiplied by a factor of  $p = 0.92 \pm 0.02$  to take into account the difference between experimental  $\tau$  branching fractions and branching fractions used in the Tauola Monte Carlo generator. With these corrected values for  $\epsilon_s$  and  $\epsilon_b$  we solve Eqs. (6a) and (6b) for each  $K^-K_S$  mass bin and obtain mass spectra for signal ( $N_s$ ) and background ( $N_b$ ).

The efficiency corrected signal mass spectrum, using the signal efficiency from Fig. 4, is shown in Fig. 10 (top), in comparison with the simulation. The  $\tau$ -pair  $m_{K^-K_S}$  background spectrum [Fig. 10 (bottom)] is compared with simulation without efficiency correction. Spectra are normalized to the same number of events. We find a substantial difference between data and simulation for the signal spectrum, and better agreement for the background spectrum.

## VII. SYSTEMATIC UNCERTAINTIES

This section lists all the uncertainties in the parameters used in this analysis, and estimates the overall systematic uncertainty on the  $\tau^- \rightarrow K^-K_S\nu_\tau$  branching fraction and the  $K^-K_S$  mass spectrum.

The subtraction of non- $K_S$  background is described in Sec. V. To check the procedure of the non- $K_S$  background subtraction, we varied the coefficients of  $\alpha$  and  $\beta$  within their uncertainties, which leads to a systematic uncertainty of 0.4% in the  $\tau^- \rightarrow K^-K_S\nu_\tau$  branching fraction. This uncertainty is independent of the  $K^-K_S$  mass.

The PID corrections were discussed in Sec. IV. The systematic uncertainty due to data-Monte Carlo simulation difference in particle identification is taken to be 0.5%, independent of the  $K^-K_S$  mass. The uncertainty on how well the Monte Carlo simulates the tracking efficiency is estimated to be 1%.

Figure 11 shows the  $m_{K^-K_S}$  spectra for selected data events with and without a  $\pi^0$  candidate near the endpoint  $m_{K^-K_S} = m_\tau$  compared to simulated  $q\bar{q}$  events. It appears that the number of data and simulated  $q\bar{q}$  events are in reasonable agreement at  $m_{K^-K_S} > m_\tau$ , where all data events are expected to be from the  $q\bar{q}$  background. We take the observed difference between data and Monte Carlo near the end point  $M_{K^-K_S} = m_\tau$  in Fig. 11 as an uncertainty on the  $q\bar{q}$  background. This leads to an uncertainty on  $\mathcal{B}(\tau^- \rightarrow K^-K_S\nu_\tau)$  of 0.5%.

The uncertainty associated with the subtraction of the  $\tau^+\tau^-$  background with  $\pi^0$ 's is estimated by varying the efficiencies  $\epsilon_s$  and  $\epsilon_b$  used in Eqs. (6a) and (6b) within their systematic uncertainties: 5% in  $\epsilon_s$  (uncertainty in the number of spurious  $\pi^0$ 's) and 6% in  $\epsilon_b$  (uncertainty in numbers of both spurious and reconstructed  $\pi^0$ 's). The corresponding contribution to the systematic uncertainty on  $\mathcal{B}(\tau^- \rightarrow K^-K_S\nu_\tau)$  is 2.3%. For the  $m_{K^-K_S}$  spectrum this



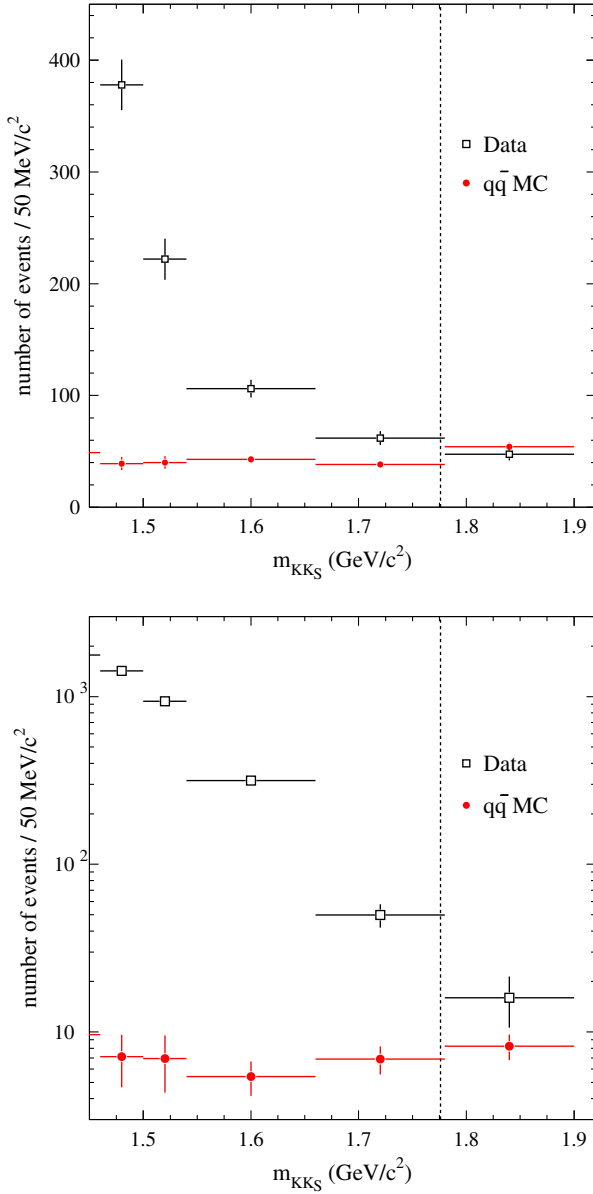


FIG. 11.  $K^-K_S$  mass spectra near the end point  $M_{K^-K_S} = m_\tau$  for selected data and  $q\bar{q}$  simulated events without (top) and with (bottom) a  $\pi^0$  candidate. The vertical line indicates the  $\tau$  mass.

uncertainty varies from 9% at  $m_{K^-K_S} < 1.1$   $\text{GeV}/c^2$  to 1% at 1.7  $\text{GeV}/c^2$ .

The 2% uncertainty in the correction factor  $p$  (Sec. VI), associated with  $\tau$  branching fractions without a  $\pi^0$ , leads to the 0.3% uncertainty in the branching ratio. The mass-dependent uncertainty is 2% at  $K^-K_S$  mass below 1.1  $\text{GeV}$  and 0.1% for 1.7  $\text{GeV}/c^2$ .

The systematic uncertainties from different sources, shown in Table I, are combined in quadrature. The total systematic uncertainty for the branching fraction  $\mathcal{B}(\tau^- \rightarrow K^-K_S\nu_\tau)$  is 2.7%. The systematic uncertainties for the mass spectrum are listed in Table II. They gradually decrease from  $\simeq 9\%$  at  $m_{K^-K_S} = 1$   $\text{GeV}/c^2$  to 1.5% at

TABLE I. The systematic uncertainties on  $\mathcal{B}(\tau^- \rightarrow K^-K_S\nu_\tau)$  from different sources.

Sources	Uncertainty (%)
Luminosity	0.5
Tracking efficiency	1.0
PID	0.5
Non- $K_S$ background subtraction	0.4
$\tau^+\tau^-$ background without $\pi^0$	0.3
$\tau^+\tau^-$ background with $\pi^0$	2.3
$q\bar{q}$ background	0.5
Total	2.7

TABLE II. Measured spectral function ( $V$ ) of the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay, in bins of  $m_{K^-K_S}$ . The columns report: the range of the bins, the normalized number of events, the value of the spectral function. The first error is statistical, the second systematic.

$m_{K^-K_S}$ ( $\text{GeV}/c^2$ )	$N_s/N_{\text{tot}} \times 10^3$	$V \times 10^3$
0.98–1.02	$5.6 \pm 1.4$	$0.071 \pm 0.018 \pm 0.006$
1.02–1.06	$26.0 \pm 2.7$	$0.331 \pm 0.034 \pm 0.026$
1.06–1.10	$46.0 \pm 3.2$	$0.593 \pm 0.042 \pm 0.042$
1.10–1.14	$70.8 \pm 3.5$	$0.934 \pm 0.046 \pm 0.056$
1.14–1.18	$84.4 \pm 3.4$	$1.148 \pm 0.047 \pm 0.057$
1.18–1.22	$92.3 \pm 3.3$	$1.309 \pm 0.046 \pm 0.052$
1.22–1.26	$98.2 \pm 3.2$	$1.468 \pm 0.048 \pm 0.044$
1.26–1.30	$98.4 \pm 3.2$	$1.569 \pm 0.050 \pm 0.042$
1.30–1.34	$96.3 \pm 3.0$	$1.663 \pm 0.052 \pm 0.042$
1.34–1.38	$90.2 \pm 2.9$	$1.715 \pm 0.052 \pm 0.039$
1.38–1.42	$87.8 \pm 3.1$	$1.873 \pm 0.066 \pm 0.039$
1.42–1.46	$65.1 \pm 2.6$	$1.597 \pm 0.064 \pm 0.032$
1.46–1.50	$57.3 \pm 2.5$	$1.666 \pm 0.073 \pm 0.032$
1.50–1.54	$38.1 \pm 2.5$	$1.361 \pm 0.090 \pm 0.023$
1.54–1.66	$36.9 \pm 2.4$	$0.785 \pm 0.049 \pm 0.013$
1.66–1.78	$6.6 \pm 10.2$	$0.986 \pm 1.520 \pm 0.014$

$m_{K^-K_S} = m_\tau$ . Near the maximum of the mass spectrum (1.3  $\text{GeV}/c^2$ ) the uncertainty is about 2.5%.

## VIII. THE RESULTS

The branching ratio of the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay is obtained using the following expression:

$$\begin{aligned} \mathcal{B}(\tau^- \rightarrow K^-K_S\nu_\tau) &= \frac{N_{\text{exp}}}{2LB_{\text{lep}}\sigma_{\tau\tau}} \\ &= (0.739 \pm 0.011 \pm 0.020) \times 10^{-3}, \end{aligned} \quad (8)$$

where  $N_{\text{exp}} = 223741 \pm 3461$  (error is statistical) is the total number of signal events in the spectrum in Fig. 12,  $L = 468.0 \pm 2.5$   $\text{fb}^{-1}$  is the *BABAR* integrated luminosity [21],  $\sigma_{\tau\tau} = 0.919 \pm 0.003$  nb is the  $e^+e^- \rightarrow \tau^+\tau^-$  cross section at 10.58  $\text{GeV}$  [10] and  $B_{\text{lep}} = 0.3521 \pm 0.0006$  is

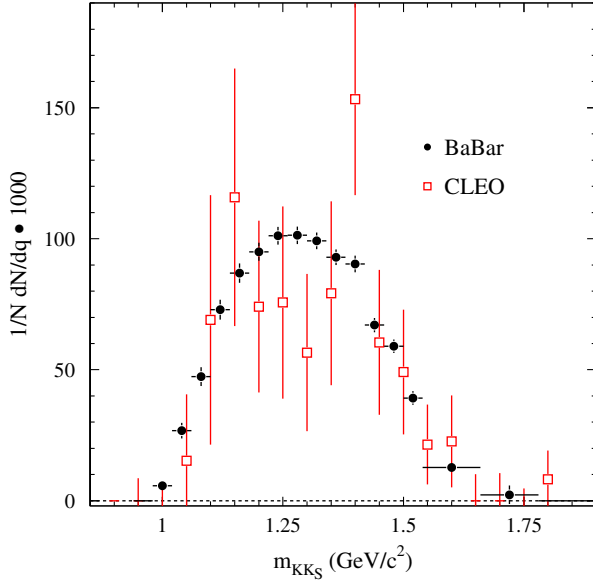


FIG. 12. Normalized  $K^-K_S$  invariant mass spectrum for the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay measured in this work (filled circles) compared to the CLEO measurement [7] (empty squares). Only statistical uncertainties are shown.

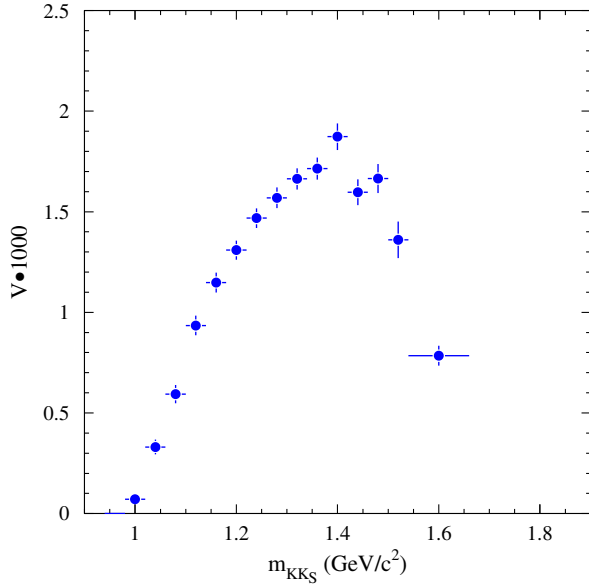


FIG. 13. Measured spectral function for the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay. Only statistical uncertainties are shown.

the world average sum of electronic and muonic branching fractions of the  $\tau$  lepton [2]. The first uncertainty in (8) is the statistical, the second is systematic. Our result agrees

well with the Particle Data Group (PDG) value  $(0.740 \pm 0.025) \times 10^{-3}$  [2], which is determined mainly by the recent Belle measurement  $(0.740 \pm 0.007 \pm 0.027) \times 10^{-3}$  [6].

The measured mass spectrum  $m_{K^-K_S}$  for the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay is shown in Fig. 12 and listed in Table II. Our  $m_{K^-K_S}$  spectrum is compared with the CLEO measurement [7]. The *BABAR* and CLEO spectra are in good agreement. The spectral function  $V(q)$  calculated using Eq. (1) is shown in Fig. 13 and listed in Table II. Due to the large error in the mass interval 1.66–1.78  $\text{GeV}/c^2$ , which exceeds the scale of Fig. 13, the value of  $V(q)$  in this interval is not shown in Fig. 13.

## IX. CONCLUSIONS

The  $K^-K_S$  mass spectrum and vector spectral function in the  $\tau^- \rightarrow K^-K_S\nu_\tau$  decay have been measured by the *BABAR* experiment. The measured  $K^-K_S$  mass spectrum is far more precise than CLEO measurement [7] and the branching fraction  $(0.739 \pm 0.011 \pm 0.020) \times 10^{-3}$  is comparable to Belle's measurement [6].

## ACKNOWLEDGMENTS

We are grateful for the extraordinary contributions of our PEP-II2 colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the U.S. Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Education and Science of the Russian Federation, Ministerio de Economía y Competitividad (Spain), the Science and Technology Facilities Council (United Kingdom), and the Binational Science Foundation (U.S.-Israel). Individuals have received support from the Russian Foundation for Basic Research (Grant No. 16-02-00327), the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation (USA).

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